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ABSTRACT

X-ray spectra for Her X-1 are presented for times before, during, and after a turn-on in the 35-day on-off cycle, as well as during an anomalous dip in the X-ray intensity. All four spectra are well-represented by a power-law of number index ∿.9 with a high energy cutoff near 20 keV. However, the column density of cold matter along the line of sight as estimated by the low energy cutoff varies substantially among the four intervals. The low level flux present prior to turn-on does not pulse and shows very little low energy absorption, in contrast to the X-rays observed during the turn-on and the anomalous dip. It seems likely that the pre-turn-on flux is composed of X-rays scattered into the line of sight by material away from the accretion disk. An accurate determination of the pulsation period for Her X-1 during August, 1975, finds the period has decreased to 1.2378065±.0000001 sec.

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I. INTRODUCTION

Her X-1 is well-known for a variety of periodic phenomena, of which the 35-day on-off cycle is the least well understood. In August, 1975, the Goddard Space Flight Center Cosmic X-ray Spectrometer on the OSO-8 satellite observed Her X-1 for $\sim$8 days, beginning 2 days before a turn-on in the 35-day cycle. Previous observations of Her X-1 have shown that the turn-on always occurs near phase 0.25 or 0.68 of the binary orbit (Giacconi et al., 1973). Such was the case in August, 1975, when the turn-on occurred at a phase of $\sim$0.23. Recently, several observers have reported weak X-ray emission from Her X-1 during phases of the 35-day cycle when the source should have been "off" (Heise and Brinkman, 1976; Fritz et al., 1976; Jones and Forman, 1976). In this paper we report a low level of X-ray flux from Her X-1 during the 2 days prior to the observed turn-on. This low level intensity was unquestionably from Her X-1 because eclipses were observed consistent with the 1.7 day binary period, although the 1.24 sec pulsations were not present.

II. EXPERIMENT and ANALYSIS

Her X-1 was observed for 8 days, the time divided between a small-angle scanning xenon-filled proportional counter for 3 days and a pointed argon-filled proportional counter for 5 days. The xenon-filled proportional counter is aligned at a five degree angle to the satellite spin axis so that it scans a five degree annulus every satellite rotation ($\sim$10 sec). For approximately 3 days between August 26.1 - 29.3, 1975, the satellite spin axis was pointed toward $RA_{(1950)} = 251.°3$, $DEC_{(1950)} = +30.°8$, so the xenon detector could observe Her X-1. Counting rates from the xenon detector were obtained in 160 msec samples so that each scan divides into ~65 azimuthal bins. A pulse height analyzer was used to divide the 2-60 keV energy range of the xenon detector in 63 channels. Energy histograms are accumulated for each quarter of a satellite revolution so that spectra can be obtained for each quadrant or sector of the scan. Background counts can thus be obtained almost simultaneously with source data. The xenon detector is collimated with copper tubes with a FWHM of 5.09 deg. The procedure for analyzing the spectral data have been described in previous papers (Pravdo et al., 1976a; Serlemitsos et al., 1973).

The xenon detector spectra of Her X-1 may be partially confused by X-ray emission from 3U1706+32. This X-ray source would contribute <.05 of the observed flux between 2-6 keV after the Her X-1 turn-on if the position and strength given in the UHURU catalog (Giacconi et al., 1974) are correct. The confusion due to 3U1706+32 is more important with regard to the interpretation of the X-ray intensity from Her X-1 prior to turn-on. During the eclipses of Her X-1 prior to turn-on some residual X-ray emission remained, indicating that as much as 10-30% of the pre-turn-on flux may be from 3U1706+32. In this paper, no attempt was made to subtract the contribution from 3U1706+32.

During the five days the argon detector observed Her X-1, counting rates were also obtained every 160 msec. Being a pointed instrument, this detector made continuous observations of Her X-1 except for periods of earth occultation and electron contamination, so that these data were well suited for measuring the 1.24 sec period of Her X-1. This was achieved by folding the counting rates after correcting the arrival times for the varying light travel time within the HZ-Her--Her X-1 binary system. The best value for the pulsation period was found by folding the data using many trial values for the period and testing each light curve against the hypothesis of a constant intensity. The period resulting in the highest χ^2 is assumed to be the actual pulsation period. The correction to the arrival times were based on a binary period of 1.7001656 $\pm$ .0000006 days and a binary orbital radius of 13.183 $\pm$ .006 light secs (Schreier, 1975). The zero phase of the binary period was a free parameter in our folding analysis, the value which maximized χ^2 taken as the best value.

III. RESULTS

Her X-1 was observed to turn-on in its 35-day cycle on Aug. 28.20 $\pm$ 0.01, 1975, with a rise time of less than 2 hours. This turn-on time occurs at a phase of 0.232 $\pm$ .006 in the binary orbit, consistent with observations of previous turn-ons which all occur near phase .25 or .68 at the binary orbit (Giacconi et al., 1973). The xenon detector on OSO-8 observed Her X-1 for 2 days before the turn-on and 17 hours after the turn-on. During the 17 hours following the turn-on, a dip in the intensity lasting $\sim$2 hours and centered at phase .61 of the binary period was observed. Therefore, the xenon-detector observed spectra representing four distinct intervals of X-ray behavior, which we will label pre-turn-on, mid-turn-on, post-turn-on, and dip.

The post-turn-on spectrum is shown in Figure 1a. This spectrum agrees very well with the spectrum observed by a GSFC rocket experiment carrying a xenon detector similiar to the detector on OSO-8 (Holt et al., 1974). The data were fit to the analytic form

$$E = C \exp(-N_H \sigma) \quad E^{-\alpha} \qquad E \leq P_3$$

$$E = C \exp(-N_H \sigma) \quad E^{-\alpha} \exp \quad (E - P_3 / P_4) \quad E > P_3$$

where σ is the energy-dependent absorption cross section by cold matter based on Brown and Gould abundances (1970) with the addition of iron, N_H is the equivalent hydrogen column density, and P_3 and P_4 describe the location and sharpness of an apparent high energy cutoff respectively. The best fit parameters and their errors (90% confidence) for the post-turn-on spectrum are given in Table 1. The post-turn-on average flux between 2-20 keV was $3.37 \pm 0.03 \times 10^{-9}$ ergs/s-cm^2.

The data for Her X-1 from the xenon detector can be well-represented by smooth spectra. However data taken with the argon detector indicate the possible presence of line emission at $\sim$ 6.5 keV (Pravdo et al., 1976b; Pravdo, 1976). When an emission feature is included in our analysis of the post-turn-on data from the xenon-data there is a significant improvement in χ^2. On this basis, we estimated an equivalent width of 340 $\pm$ 300 eV (90% confidence) for an emission feature at $\sim$ 6.5 keV.

We found that the spectra during the mid-turn-on and dip periods can be fit by the same continuum spectrum found for the post-turn-on period with additional low energy attenuation. The mid-turn-on and dip spectra are shown in Fig. 1b and 1c respectively and their spectral parameters are given in Table 1. During the dip an iron edge is apparent in the spectrum. In addition to low energy absorption, both the mid-turn-on and dip spectra show a drop of $\sim$ 30% in overall intensity, perhaps due to Compton scattering. Such a decrease would indicate a column density of free electrons N_e of $\sim 5 \times 10^{23}/cm^2$. This is consistent with N_H calculated for the dip spectrum but high compared to N_H found from the mid-turn-on data, suggesting the presence of highly ionized material which does not contribute to the low energy absorption.

The incident spectrum accumulated prior to turn-on between Aug. 26-27, 1975, is shown in Fig. 1d. This spectrum is qualitatively the same as the post-turn-on spectrum but at a much reduced intensity. Again number index α and N_H are given in Table 1. There is some indication of an absorption edge in the pre-turn-on spectrum at $\sim$ 8 keV. The 2-20 keV flux was $2.09 \pm .13 \times 10^{-10}$ ergs/s-cm^2, 6.2% of the post-turn-on flux. If the reduction in intensity from the post-turn-on state is due to Compton scattering, the column density of electrons Ne is $\gtrsim 4.2 \times 10^{24}/cm^2$. The pre-turn-on spectrum observed is consistent with being the same as the post-turn-on spectrum reduced in intensity by Compton scattering. During the pre-turn-on period, the 1.7 day eclipse behavior was still apparent in the data, assuring that most of the observed flux originated from Her X-1. However, some X-rays from 3U1706+32 may be included.

Folding the data from the argon detector for its entire five day observation of Her X-1 allows a very accurate determination of the pulsation period. During the five day period August 29.03 - September 3.49, 1975, we measured a pulsation period of 1.2378065 ± 0.0000001 sec. The best estimate of the zero phase of the binary orbit from the same analysis is August $29.5059 \pm .0005$, 1975. This pulse period indicates that the spin-up of the Her X-1 pulsar detected by UHURU (Tananbaum et al., 1972) has continued. The value found for the zero phase of the binary orbit is delayed by 0.0017 days relative to that expected by the extrapolation of UHURU results (Schreier, 1975). Although the disagreement is only a two sigma effect, it does suggest that the binary period of Her X-1 is increasing. Such behavior has been observed for Cen X-3 (Tuohy, 1976).

Using the pulse period and binary orbital phase found from the argon detector data, the xenon detector counting rates were folded on the pulse period. The pulsations are clearly present in the post-turn-on interval with a measured pulsed fraction of .38. The pulsations are also present during the turn-on and during the anomalous dip. However, there is no indication of pulsations during the pre-turn-on interval. Assuming that if the pulsations were present in the pre-turn-on interval, they would be in phase with the post-turn-on pulsations, allows us to place a 3 sigma upper limit of .051 on the pulsed fraction prior to turn-on. If we assume that the X-rays from the compact object are pulsed with a pulsed fraction of $\sim$ .38, but that the X-rays are being scattered by free electrons along the line of sight, than the upper limit to pulsations implies that less than .134 of the X-rays we receive are unscattered, indicating an optical depth of at least $\sim$4.8 due to a column density of free electrons N_E of $\gtrsim$ $7.1 \times 10^{24}/cm^2$. If we relax the condition that any pulsations prior to turn-on are in phase with those after turn-on, then the upper limit for the pulsed fraction increases to .064.

IV. DISCUSSION

The spectral behavior of Her X-1 during the post-turn-on and dip phases is very similar to that of other eclipsing X-ray binaries, and in particular to 3U0900-40. The unabsorbed spectrum of 3U0900-40 is also characterized by a power law, with a cutoff (Rothschild et al., 1976) at a somewhat higher energy than that of Her X-1. The sharp break in the spectrum of Her X-1, which was first noted by Holt et al. (1974), is confirmed by the OSO-8 data. Boldt et al. (1975) interpreted the cutoff in Her X-1 in terms of the energy dependence of the severely modified Thomsom scattering that dominates the radiative transfer in a highly magnetized plasma near the poles of a neutron star. This interpretation leads to a linear relation between the cutoff energy and the strength of the magnetic field, so that the ratio of the cutoff energies between Her X-1 and 3U0900-40 may indicate the relative field strengths at the two sources. If the modified Thomson scattering mechanism is the cause of the high energy cutoff, and if the radiated flux carried away by the extraordinary wave relative to that carried away by the ordinary wave is as estimated by Basko and Sunyaev (1975), then we expect the ratio between our spectral parameters P3 and P4 to be within the range 2.4 - 2.7, depending only upon the relative abundances of the elements responsible for stopping the accreting matter. This permissible range is in good agreement with the observed ratio for both Her X-1 and 3U0900-40. That the high energy cutoff (P_4) remains the same during all phases observed indicates that this pronounced feature is linked to some strong intrinsic property of the compact object itself. Therefore, a high magnetic field near the poles of a neutron star provides a plausible basis for such an effect.

The 35-day on-off cycle of Her X-1 is unique among the known X-ray binary systems. Petterson (1975) has suggested that the X-ray luminosity of the compact object is independent of the 35-day cycle and that the on-off behavior results from the periodic obscuration of the compact object by a twisted accretion disk. Jones and Forman (1976) also concluded that the 35-day modulation is due to the changing orientation of an accretion disk, although they favored the "slaved" disk model of Roberts (1974) and Gerend and Boynton (1976). The models of Petterson and of Roberts differ in the assumption of whether the inward spiral time for gas in the accretion disk is long or short, respectively, when compared to 35 days. The slaved disk model does not seem to explain why Her X-1 turns on sharply and off gradually, whereas the twisted disk model does (Petterson 1975). Our observations show no indication that the intrinsic X-ray emission from the compact object varies (cf. Lamb et al., 1973). Rather, all changes in the X-ray spectrum and intensity we observe can be understood as variations in the absorption and scattering of flux from the compact object.

The absence of low-energy absorption in the spectrum prior to turn-on indicates that this flux passes predominantly through gas in which mediumweight elements such as oxygen are highly ionized, either by X-ray photoionization or by collisional ionization (see Hatchett et al., 1976). The collisional case would require a gas temperature $\gtrsim 10^7$ K to strip oxygen. If the iron edge at $\sim$ 8 keV is real, the edge energy implies iron is partially but not fully ionized, since the iron K-edge varies from 7 to 9 keV as electrons are stripped off. This middle range of ionization states is consistent with a temperature of 10^7 K as well as with a photoionizing flux strong enough to strip oxygen.

It seems likely that the pre-turn-on flux is composed of X-rays scattered into the line of sight by material away from the accretion disk. The lack of pulsations prior to turn-on indicate that the optical depth τ along the direct line of sight through the disk due to Compton scattering is >4.8. However, Illarionov and Sunyaev (1972) have discussed the distortions which will occur to a spectrum such as that of Her X-1 when such a spectrum is observed through an electron gas of $kT << h\nu$ The primary effect is a depletion of X-rays of energy $E \geq M_e C^2/\tau^2$. Lack of distortion in the pre-turn-on spectrum indicates that the optical depth $\tau < 3$, much less than the optical depth through the disk.

The spectra during mid-turn-on shows significant low energy attenuation attributable to photoelectric absorption, implying the presence of cool material at the outer regions of the accretion disk. If the pre-turn-on flux were coming through the disk, it would also suffer photoelectric absorption. The lack of any appreciable low energy absorption in the pre-turn-on spectra is another indication that the X-rays are not traversing the accretion disk.

If the pre-turn-on flux is being scattered by material away from the accretion disk, the material must be local to Her X-1 because the scattered flux is eclipsed by Hz Her. Consider the case of a spherical gas cloud of constant density n_c and radius r_c, centered on Her X-1. If Her X-1 is assumed to radiate isotropically, then the 2-20 keV luminosity L 10^{37} erg s^{-1} for a source distance of 5 kpc. Since the X-ray emission from Her X-1 is non-isotropic, let fL be the true X-ray luminosity of Her X-1. Then the magnitude of the observed pre-turn-on flux, 2×10^{-10} ergs $s^{-1}cm^{-2}$, implies $n_c r_c \sim 9 \times 10^{22}$ f^{-1} cm^{-2}. Since r_c must be less than the radius of H_Z Her ($\sim 3 \times 10^{11}$ cm), $n_c \geq 3 \times 10^{11}$ $f^{-1}cm^{-3}$. The most inefficient spherically symmetric mass distribution for scattering would be a shell of electrons around Her X-1 with a radius equal to the radius of H_z Her, so there must be fewer than $9 \times 10^{46}f^{-1}$ electrons in the scattering cloud if the electron distribution is spherically symmetric. The number of scattering electrons could be much greater for non-symmetric distributions. Possible sources for the scattering material are gas expelled from the inner disk by flares or instabilities (e.g. Lightman, 1974) and a hot corona surrounding the outer disk (Shakura and Sunyaeu, 1973).

In contrast to the low intensity observed prior to turn-on, the decrease in intensity and the low energy absorption observed during the dip at binary phase .61 can be explained by an increase of cold matter with normal cosmic abundances along the line of sight. Dips in the X-ray intensity of Her X-1 are known to occur regularly with a period of 1.62 days (Jones and Forman, 1976), which corresponds to a beat frequency between the 1.7 and 35 day periods. These dips are usually attributed to absorption by material streaming between the primary and compact stars. However, the dip we see on Aug. 28 is out of phase with the normal sequence of dips, and is in fact an extra dip. UHURU observed two such extra dips in April and July, 1972, also occuring at binary phase ~ 0.6 immediately following a turn-on at binary phase 0.25 (Giacconi et al., 1973).

It is possible that these extra dips always occur after a turn-on at phase ∿ 0.25 and are caused by a stable feature at the outer edge of the accretion disk. If a similar dip were to occur following turn-on at phase ∿ 0.68 it would occur during eclipse and hence be unobservable.

Our determination of the pulse period confirms that Her X-1 continues to undergo spin-up. UHURU data from between 1972 - 1973 showed both positive and negative changes in the period with an overall spin-up over the interval (Tananbaum et al., 1972). The addition of our observation shows that although over short intervals of time (several months) both increases and decreases in the spin period occur, over long intervals (∿ 4 years) the compact object is spinning up.

In summary, we conclude that the 35-day, on-off cycle of Her X-1 results from gross aspects of the disk configuration and is completely independent of phenomena occurring at the compact object. The data show no indication that the X-rays intrinsic to the compact object vary with respect to the 35-day cycle. These results are in accord with the twisted accretion disk proposed by Petterson (1975). The occurrence of an anomalous dip following turn-on similiar to those observed by Giacconi et al. (1973) indicates these dips are associated with the 35-day cycle. The suggested presence of a scattering medium above the accretion disk should have observable consequences. In particular, the eclipses of Her X-1 by H_Z Her should not by total; rather, some scattered flux should be present at the beginning and end of the eclipses.

FIGURE CAPTIONS

Fig. 1 Incident X-ray spectra for Her X-1. a) post-turn-on interval (top left); b) mid-turn-on interval (top right); c) anamolous dip (bottom left); d) pre-turn-on interval (bottom right). The solid line in each graph represents the best fit power-law with parameters given in Table 1.

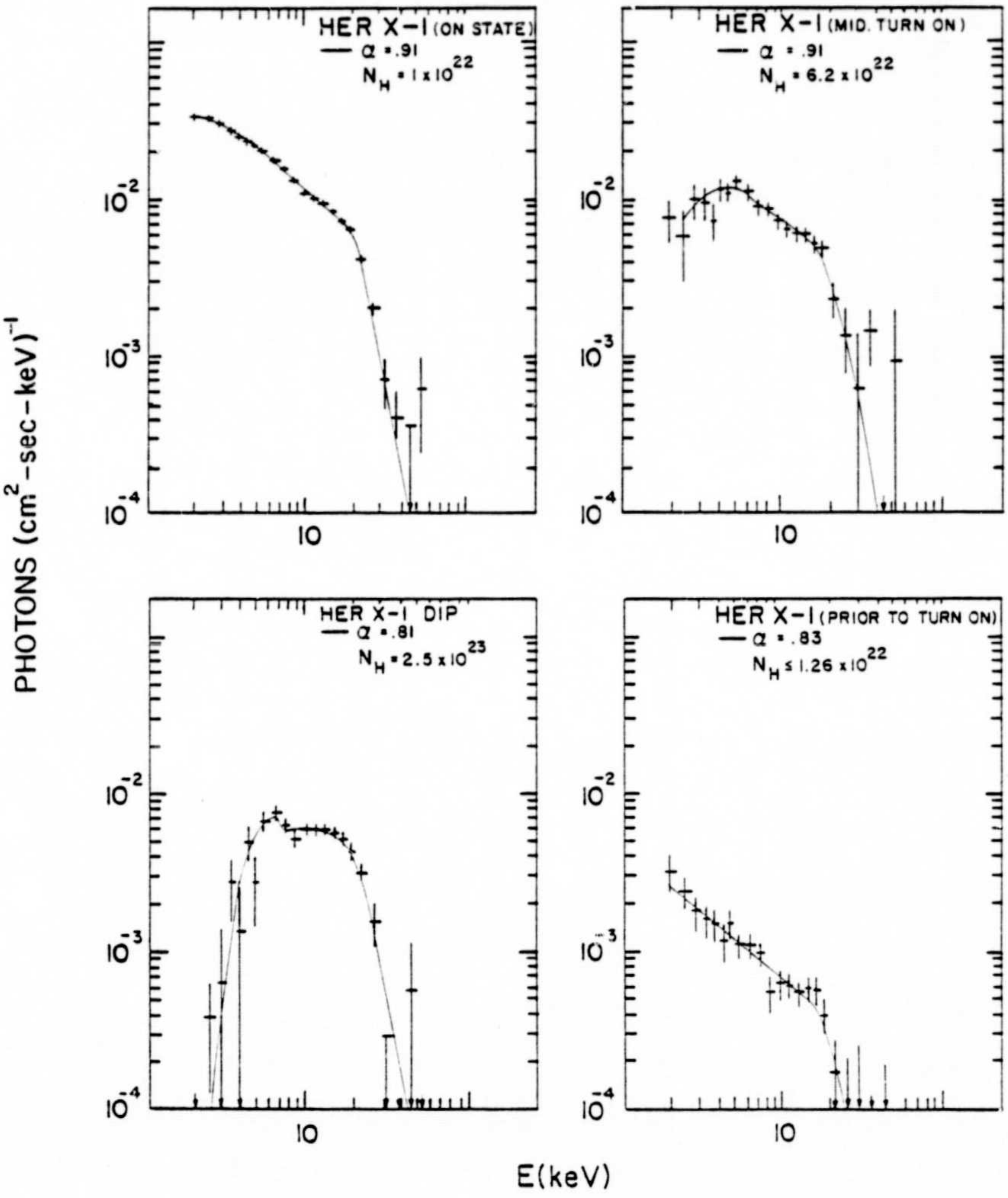
HER X-I (ON STATE)
— α = .91
N_H = 1 x 10^22
HER X-I (MID. TURN ON)
— α = .91
N_H = 6.2 x 10^22
HER X-I DIP
— α = .81
N_H = 2.5 x 10^23
HER X-I (PRIOR TO TURN ON)
— α = .83
N_H ≤ 1.26 x 10^22
PHOTONS (cm^2-sec-keV)^-1
10^-2
10^-3
10^-4
10
E(keV)

TABLE 1

SPECTRAL PARAMETERS FOR HER X-1

SPECTRUM	NUMBER INDEX α	COLUMN DENSITY N_H (cold matter) atoms/cm^2	P{3}(keV)	P{4}(keV)	χ^2/Deg. of Freedom
post-turn-on	0.91 ± 0.05	$1. \pm 0.4 \times 10^{22}$	$19.7^{+1.4}_{-1.7}$	$7.3^{+3.6}_{-2.4}$	22.6/18
mid-turn-on	0.91^*	$6.2^{+2.8}_{-1.7} \times 10^{22}$	19.7^*	7.3^*	23.5/21
pre-turn-on	$0.85 \pm .25$	$0 + 1.26 \times 10^{22}$	19.7^*	7.3^*	9.9/20
dip	0.91^*	$2.9^{+.8}_{-.4} \times 10^{23}$	19.7^*	7.3^*	23.4/21

*not used as a free parameter

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